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The effects of concurrent biomechanical biofeedback on rowing performance at different stroke rates

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ABSTRACT

The aims of this study were to assess the effects of stroke rate (SR) on the ability of trained rowers to: a) comply with concurrent biomechanical biofeedback on knee-back-elbow joint sequencing; and b) transfer any changes to competition-intensity conditions (maximal rowing task). Following a five-minute maximal rowing task (Baseline), 30 trained rowers were randomised to four groups. Two groups rowed at high SRs (90% maximum SR with biofeedback (BFb_{90}) or control), while others rowed at low SRs (60% maximum SR with biofeedback (BFb_{60}) or control) for 3 sessions. All rowers then completed another maximal rowing task (Transfer). Rowers complied with the biofeedback at both SRs, which promoted coordinative changes to knee-elbow motions during the pull. During Transfer, control rowers did not improve whereas those receiving biofeedback covered significantly greater distances (increase from Baseline: BFb_{60} = 6 ± 5%; BFb_{90} = 5 ± 4%; $p < 0.05$). However, movement adaptations were temporally different between SRs and were better maintained into Transfer by those that rowed at higher rates. This indicated biofeedback specificity, as transference of modified movement patterns appeared better when acquisition and transfer conditions were similar. These findings have practical implications for assimilating biofeedback into training programmes.

ARTICLE HISTORY
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KEYWORDS
CI2; coordination; feedback; real-time; training

1. Introduction

Augmented feedback can be split into two classifications. Knowledge of results pertains to information regarding the success of an action with respect to a set outcome, or the extent to which an intended goal is accomplished (Schmidt & Lee, 2005). In contrast, knowledge of performance (KP) provides information on how the outcome was achieved (Schmidt & Lee, 2005), which can comprise biomechanical biofeedback on the kinetics or kinematics of a desired movement pattern.

In rowing, the "Rosenberg" technique is considered the most powerful style and is characterised by sequential body segment movements (Klavora, 1977; Kleshnev, 2010). On an ergometer, limited trunk movement and more extended elbows (>150°) during the early stages of the pull aids transference of forces generated by the legs to the handle (Bompa, 1980; Pollock et al., 2009). Lower limb contribution to handle velocity is surpassed by that from the trunk at approximately 40% of the pull, which is followed by joint rotations of the upper limbs from around 70% of the pull until the finish (Klavora, 1977; Kleshnev, 2010; Lamb, 1989). As kinematic technique changes are apparent at different stroke rates (SRs; McGregor et al., 2004), refinement of body segment coordination is of considerable importance. Achieving this could be aided by providing KP on the timings of key joint rotations in the form of concurrent biomechanical biofeedback.

While performing rowing-type tasks at lower SRs, the provision of KP biofeedback has improved relative body segment sequencing (Gorman et al., 2019), boat acceleration profiles (Schaffert & Mattes, 2014), and spatial-temporal consistency of the oar-handle path (Sigrist et al., 2013). Biofeedback has also successfully enhanced the stroke consistency (Anderson et al., 2005) and the power output of more skilled rowers while performing maximally (Spinks & Smith, 1994). Although these studies show the benefits of biofeedback for training rowing-type tasks and rowing technique, they have only been conducted while exercising at either submaximal or maximal intensities. The ability to comply with the same kinematic biofeedback whilst rowing at different SRs or intensities is unknown.

The effectiveness of biofeedback has been explained using the guidance hypothesis (Salmoni et al., 1984; Schmidt, 1991), whereby a learner is directed towards a desired technique or outcome, allowing them to attend to errors in their movement (Shan et al., 2014). As predicted by the guidance hypothesis, rowers may develop a dependency on KP biofeedback, such that decrements in performance are seen upon its removal. Despite initial performance enhancements, Schaffert et al. (2011) reported that immediately after acoustic biofeedback on boat velocity was turned off, no significant differences from baseline measures were apparent, and although Sigrist et al. (2013) improved oar trajectories during delayed retention tests, the effects were reduced for visual as compared to acoustic and haptic biofeedback modalities. Many rowing biofeedback studies neglect to test this dependency concern (e.g., Anderson et al., 2005; Gorman et al., 2019; Lintmeijer et al., 2019). Consequently, the efficacy of such interventions beyond

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immediate task acquisition, and the practical implications of biofeedback for performance, remain uncertain.

Despite the positive isolated benefits of biofeedback-enhanced rowing training (e.g., Gorman et al., 2019; Schaffert & Mattes, 2014), a changing ability to comply with the information at different SRs could limit the integration of biofeedback into training regimes. The effects of biofeedback also need to be reproducible both after its removal and while performing under conditions that replicate actual rowing performance (i.e., at maximal SRs). According to the specificity of learning, adaptations are specific to the feedback sources available during complex task acquisition (Blandin et al., 2008; Proteau et al., 1992; Ranganathan & Newell, 2009). As SR is a key specificity of rowing (McGregor et al., 2004), the transfer of biofeedback-induced changes to different SRs or maximal intensity rowing may be influenced by the SR at which they were acquired. As such, the aims of this study were to assess the effects of the SR of a rowing task on the ability of trained rowers to a) comply with concurrent biomechanical biofeedback, and b) transfer technique changes to higher-intensity conditions. It is hypothesised that rowing at different SRs would promote different kinematic changes to the stroke, and that modifications would be better retained during competition-intensity transfer testing if they were developed at higher SRs.

2. Materials and methods

2.1. Participants

Thirty participants (mean ± standard deviation (SD); age, 22 ± 3 years; height, 171.2 ± 5.2 cm; mass, 69.1 ± 6.7 kg; male, $n = 8$, female, $n = 22$) were recruited. Inclusion criteria were that participants were free from injury, had ergometer rowing experience of at least one year, and were regularly training and competing in rowing at the time of the study. Institutional Ethical Committee approval for the study was granted prior to its commencement, and each rower gave written informed consent before participating.

2.2. Data collection

Each rower was randomly assigned to one of four groups, two of which received concurrent biofeedback on their technique (BFb_{90}, $n = 7$; BFb_{60}, $n = 7$), and two of which did not (Con_{90}, $n = 9$; Con_{60}, $n = 7$), where *BFb* is biofeedback, *Con* is Control, and *90* and *60* represent SRs of 90% ±2 strokes-per-minute, and 60% ±2 strokes-per-minute of mean SR over the first visit (Baseline). All participants visited the laboratory on 5 occasions, evenly spaced over a 2-week period. During each visit, rowers performed a self-selected, rowing-related warm-up before rowing continuously for 5 min. Three-dimensional kinematics were recorded for the duration of each session at a rate of 150 Hz using eight Raptor-E and three Raptor-4 Digital Cameras (Motion Analysis Corporation (MAC), Santa Rosa, CA).

During Baseline, all participants rowed at maximal volitional effort, aiming to row as far as possible. Throughout and after Baseline, except for SR, neither information from the Performance Monitor (PM4; Concept2 Ltd.) that was mounted to the ergometer was visible nor biomechanical biofeedback were provided whilst rowing. For three consecutive intervention sessions (the last of which was termed S3), each group rowed at different SRs.

Rowers in both *BFb* groups were given a standardised information sheet about the content and protocol of the biofeedback intervention. During rowing, concurrent biofeedback was provided intermittently for alternate 30 s periods, beginning 30 s after the start of the trial. Neither control group received any biofeedback. Transferability of adaptation brought about during the intervention was assessed through a final visit (Transfer) that followed the same protocol as Baseline, where participants rowed maximally, and no groups received biofeedback or technique instruction.

To track ergometer motion, passive, spherical, retro-reflective markers of 9.5 mm diameter were attached to the right-side of a slide-based, Dynamic indoor rowing ergometer (Concept2 Ltd., Morrisville, VT). These included on the handle where it joined the pulley cable, the foot stretcher and seat, and the centre slider stop. To track joint motions, markers were affixed to each participant over the: lateral epicondyle of the right humerus; right ulnar styloid process; lateral epicondyle of the right femur; right lateral malleolus; first (L1) and fifth (L5) lumbar vertebrae; and bilaterally over the acromion process, greater trochanter, and posterior superior iliac spine. Additional markers were placed on the lateral sides of the upper and lower arm and the upper and lower leg to aid joint marker tracking (Figure 1(a–d)).

The origin of the global coordinate system was at ground level, below the centre of the ergometer slider stop and was orientated so that the X-axis ran horizontal and parallel to the long axis of the ergometer, towards the pulley system, the Z-axis was vertical and the Y-axis was the cross product of Z and X (Figure 1(c,d)). The concurrent biofeedback was projected onto a screen in front of the ergometer, which participants could view without altering their technique (Figure 1(e)).

All marker identifications were completed using Cortex (v5.3.1.1543; MAC). Data were further analysed using custom written MATLAB code (R2020b; MathWorks, Natick, MA). Coordinate data were smoothed using a zero-lag, 4th order Butterworth low-pass filter with a cut-off frequency of 7 Hz. For the biofeedback, which was generated using custom-written Sky script (Cortex v5.3.1.1543, MAC), position and velocity data of the ergometer markers were taken from Cortex. Ergometer measurements were conducted in the sagittal plane and joint angle data were calculated in three dimensions (3D) as follows. The elbow angle was the angle between a vector running from the lateral elbow marker to the acromion marker and a vector running from the lateral elbow marker to the lateral wrist marker, with 180° indicating full extension. The spine angle was the angle between a vector running from the L5 marker to the L1 marker and a vector as the positive X-axis; with 90° indicating that the spine was perpendicular to the X-axis. Forward inclination of the spine towards the feet (<90°) was termed flexion; backwards inclination (>90°) was termed extension. The knee angle was the angle between a vector running from the lateral knee marker to the greater trochanter marker and a vector running from the lateral knee marker to the lateral ankle marker, with 180° indicating full extension.

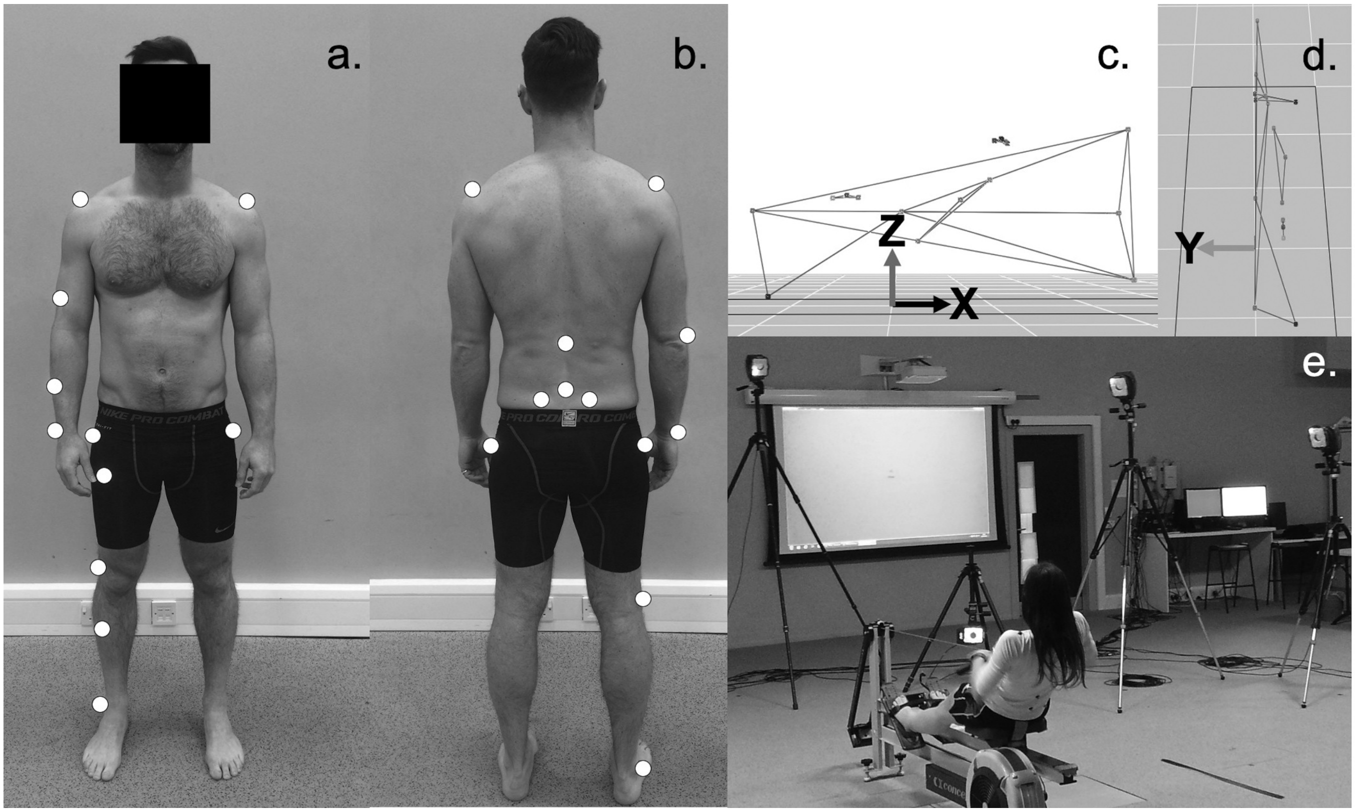

Figure 1. Participant marker placement sites from (a) anterior and (b) posterior views. Sites are circled and highlighted. Also shown are locations of markers attached to the Dynamic ergometer and the origin and orientations of the global X, Y, and Z-axes, as seen on the motion capture template (c and d). Further depiction of ergometer position and orientation relative to the biofeedback screen is shown in (e). The clothing in (e) was not representative: during all data-collection sessions, markers were affixed directly to the skin or to tight-fitting clothing.

Two key events were defined as the instants at which the velocity of the ergometer handle in the X-axis changed from positive to negative (catch), and from negative to positive (finish). These were used to define the "pull" (catch to finish) and "recovery" (finish to catch) phases, and the combination of one pull and the following recovery constituted one rowing stroke. For the set-up of the biofeedback, a normalised expected stroke displacement was calculated as 83% of each rower's body height (Černe et al., 2013). When rowing, instantaneous stroke displacement was calculated as the total of handle and foot stretcher marker movements from their respective starting positions at the catch. This was presented at each instant as a percentage of the expected stroke displacement.

2.3. Biofeedback content

For the content of the biofeedback, based on work by Lamb (1989), the pull phase was divided into three sub-phases (I, II, and III), lasting 40, 30 and 30% of the expected stroke displacement, respectively. For each stroke, biofeedback was initiated at the catch and was provided whilst the handle velocity was in the negative X-axis direction (i.e., backwards). During each sub-phase respectively, the text "Knee", "Spine" or "Elbow" was projected onto the screen in front of the participant, with background colours of gradually lighter shades of green (Figure 2). To promote delayed elbow flexion to refine the desired kinematic sequencing, maintenance of an elbow angle more than 130° was required over the first two sub-phases (i.e., 0–70% of the pull). If rowers complied with maintaining increased elbow extension, "Knee" then "Spine" would appear during each of sub-phases I and II, providing instruction for these joints to be used to produce ergometer movement. If an elbow angle greater than 130° was maintained into sub-phase III, "Elbow" would appear until the end of the current pull. The instant the elbow angle dropped below 130° during either sub-phase I or II, the screen turned red and informed participants that the "elbow flexed too early", which was displayed until the end of the pull (Figure 2). The biofeedback was restarted at the next catch. Furthermore, if at any time during the pull the sign of the handle marker velocity returned to being positive, or instantaneous stroke displacement exceeded the expected stroke displacement, the biofeedback switched to blue. For the duration of each recovery phase, the text "Recovery" was displayed on a blue screen (Figure 2). To help maintain the target SR, the current SR (strokes-per-minute) was always displayed on the coloured biofeedback screen. This was calculated using the duration between the previous two catches.

2.4. Data analysis

All variables were calculated from the first 10 consecutive strokes immediately after the midpoint of each session. As transitioning between receiving biofeedback and not receiving biofeedback can affect kinematics (e.g., Schaffert et al., 2011), these strokes were taken from periods that did not overlap

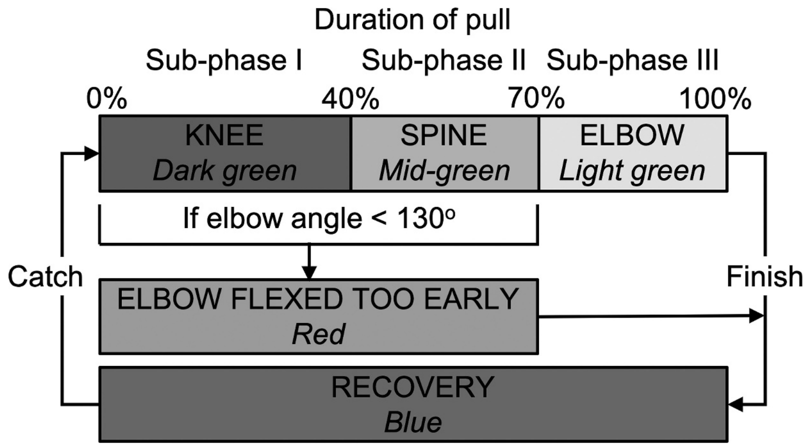

Figure 2. Schematic diagram of the biofeedback intervention given during the rowing task. Information regarding knee, spine, and elbow motion was displayed by dialogue boxes, projected in front of the participant. If at any point during the first 70% of the pull phase the elbow angle was < 130°, a different dialogue box was displayed until the recovery phase was reached. Dialogue boxes were displayed with different background colours, as indicated.

biofeedback and non-biofeedback periods. For each *BFb* group during S3, biofeedback was present when these strokes were taken, whereas in Baseline and Transfer, biofeedback was not present. Additionally, strokes from the mid-point of each session were analysed so that the rowers had time to achieve steady-state exercise, while avoiding possible changes to spinal kinematics due to fatigue towards the end of each session (Holt et al., 2003).

To account for inter-rower differences in times to complete the pull, data were time normalised by cubic spline interpolation to 101 samples-per-pull, and discrete values were expressed as percentages of each time-normalised pull, where 0% represented the catch and 100% represented the finish. These data were used to quantify changes in coordination between elbow and knee motions through assessment of alterations made to the timings and magnitude of their relative motions during the pull, bivariate analysis of these joints was conducted using 'CI2' (Mullineaux, 2017). On bivariate knee-elbow angle-angle plots from each of the Baseline, S3, and Transfer sessions per participant, the 10 consecutive rowing strokes taken were detrended by removing the mean angle from all data points and 95% confidence intervals (CI) were created using ellipses and quadrilaterals at each time point. For each participant, Baseline v S3, Baseline v Transfer, and S3 v Transfer comparisons were made, and pairs of bivariate CI bands for each individual comparison were plotted (e.g., Figure 3). Assessment of the overlap of the CIs at the same time, or ± 5 frame time-lag, chosen based on the expected temporal change in the elbow angle (Gorman et al., 2019), indicated where the two time-series differed. Shaded areas indicated where CIs of the time series data overlapped and thus were similar, while periods of non-overlap were white and indicated differences between the series. In addition, periods of CI overlap for individual participant comparisons were plotted by the group to ascertain any temporal agreement between the CI overlap periods, which indicated group similarities and differences in the changes between strokes (e.g., Figures 4 and Figure 5). Horizontal lines indicated where individual CI comparisons overlapped, while breaks in the lines indicated where the series differed. Vertical shaded portions of the plots showed where CI overlap was the same for >5 participants, and unshaded portions indicated ≤5 of the group had CI overlap. Rowing performance was determined by the distance rowed (*Dist*) during each session, ascertained from the Performance Monitor on the ergometer. Changes in distance rowed (δ) were each expressed as percentage differences to the distance rowed during Baseline.

2.5. Statistical analysis

Inferential statistical analyses were also performed using SPSS (v.27; IBM, Armonk, NY) to compare between groups (*BFb, Con*), SRs (60, 90) and sessions (Baseline, S3, Transfer) using three-way mixed ANOVA. Data were not normally distributed (Shapiro-Wilk test, $p < 0.05$), but as the group sample sizes were approximately equal the ANOVA remains robust to violations of the normality assumption (Field, 2013). Interactions were supported by partial eta squared effect sizes (η_p^2) that were interpreted as: small, 0.01–0.06; medium, >0.06–0.14; and large, >0.14 (Cohen, 1988; Richardson, 2011). Significant interactions were further explored using analyses of simple main effects and least squared differences, and paired comparisons presented as Cohen's *d* effect sizes interpreted as: small, 0.2–0.5; medium, >0.5–0.8; and large, >0.8 (Cohen, 1988). A statistical significance level of 0.05 was used for all statistical analyses, and data were presented as means ± SDs.

3. Results

3.1. Individual coordination patterns

As examples of individual CI2 analysis, sample bivariate plots are displayed for one participant from each group (Figure 3). The chosen biofeedback participants were considered to have complied with the intervention, whereas rowers in control groups showed little difference across sessions.

For participant 6 in the BFb_{90} condition ($BFb_{90}P6$), spatial and temporal changes in the dynamics of elbow and knee motions from Baseline into S3 were observed. This was

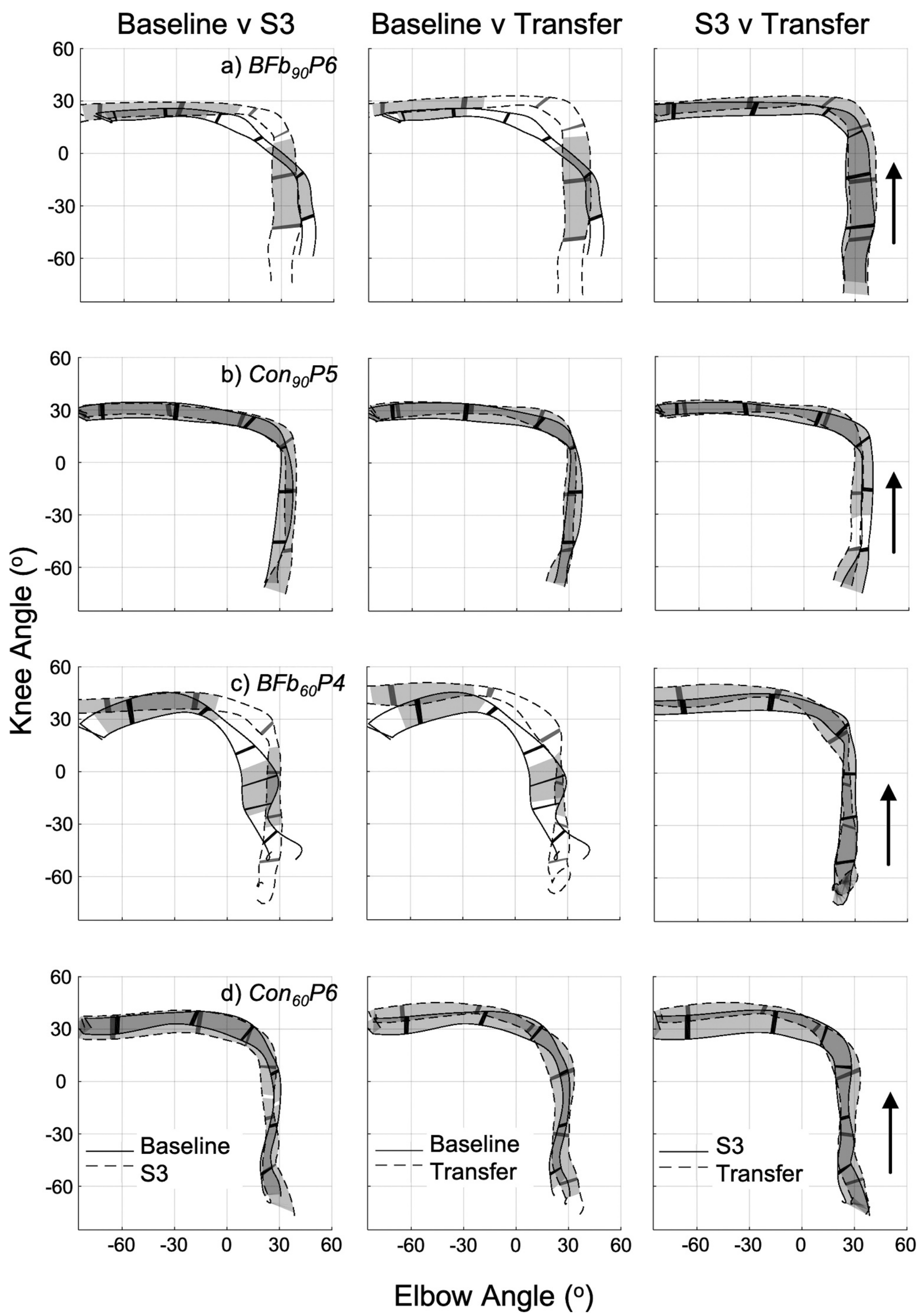

Figure 3. Knee-elbow angles bivariate plots for pairs of comparisons of data collection times for four selected biofeedback (a, *BFb$_{90}$P6*; c, *BFb$_{60}$P4*) and control (b, *Con$_{90}$P5*; d, *Con$_{60}$P6*) participants. Column: 1 shows Baseline v S3 pairs; 2 shows Baseline v Transfer pairs, and; 3 shows S3 v Transfer pairs. Solid and dashed lines represent the 95%CI for each part of the pair. Time-periods of overlap are shaded (light for part 1 of pair, or medium-light grey part 2 of the pair) and periods of non-overlap are white. Highlighted quadrilaterals at certain time-points represent intervals every 15% of the normalised pull for the part 1 of the pair (black) and part 2 of the pair (medium-dark grey), which illustrates temporal alignment between the time-series. Directional arrows on the right column indicate movement from the catch towards the finish for all graphs. Minimum values are knee flexion and elbow flexion.

exemplified by the periods of non-overlap of the CI (white) over the first 23% and between 43 and 68% of the pull (Figure 3(a), column 1). The coordination pattern moved towards that promoted by the biofeedback with elbow flexion beginning later in the pull. During Transfer, movement patterns displayed similar divergences from Baseline as they did during S3 (Figure 3(a), column 2). As no differences were apparent in the S3 v Transfer comparison (Figure 3(a), column 3), the modified movement pattern appeared to be maintained into Transfer and no return towards Baseline patterns was observed after the removal of the biofeedback. The knee-elbow motion of *Con$_{90}$P5* remained similar across each comparison (Figure 3(b)). Except for the period 16–23% of the pull phase for S3

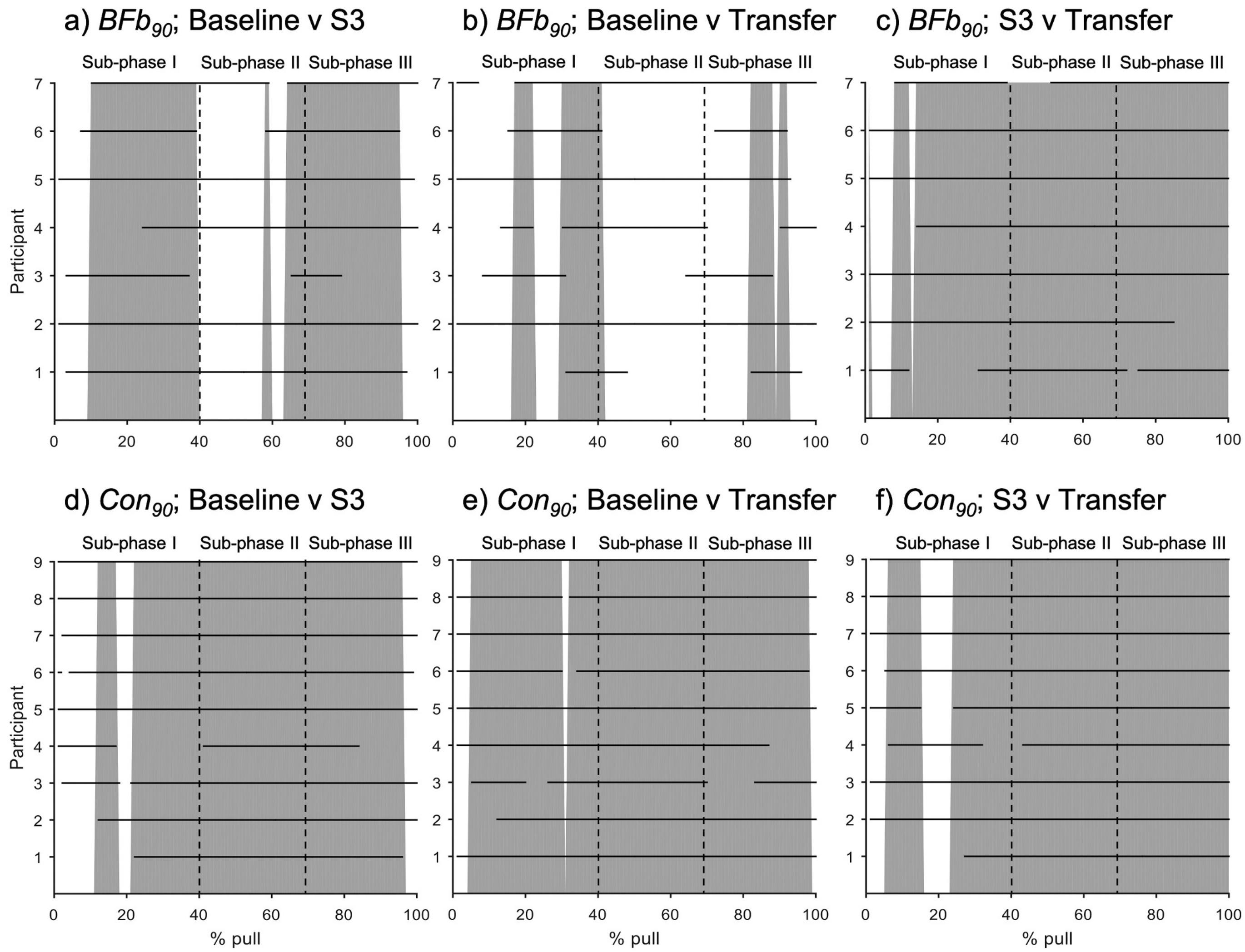

Figure 4. Periods of CI overlap of knee-elbow angle-angle plots for each participant for the high stroke rate (90%) pair comparisons of: (a) BFb_{90}, Baseline v S3; (b) BFb_{90}, Baseline v Transfer; (c) BFb_{90}, S3 v Transfer; (d) Con_{90}, Baseline v S3; (e) Con_{90}, Baseline v Transfer; (f) Con_{90}, S3 v Transfer. Solid horizontal lines indicate overlap between the pair comparisons. Shaded regions indicate where >5 participants have the same temporal overlap, while black shading indicates >5 periods of non-overlap (note, there were no occurrences). Dashed vertical lines represent transitions between pull sub-phases (0–40%, Sub-phase I; 40–70%, Sub-phase II; 70–100%, Sub-phase III).

v Transfer, coordination patterns were consistent, implying little overall change to knee-elbow motion. For $BFb_{60}P4$, Baseline v S3 coordination differences were apparent mainly for the first 33% and between 55 and 77% of the pull (Figure 3(c), column 1). Changes in sub-phase I were attributable to delayed elbow flexion, like those of $BFb_{90}P6$. Furthermore, a more extended position of the knee whilst the elbow was continuing to flex was also apparent over the latter part of the pull. The periods of CI difference between the Baseline v Transfer comparison (Figure 3(c), column 2) were consistent with the differences of Baseline v S3. This shows coordinative adaptation in line with the biofeedback over the acquisition period and demonstrates little reversion to the coordination pattern of Baseline during Transfer after the removal of the biofeedback. High CI overlap for each comparison indicated that coordination patterns were consistent for $Con_{60}P6$. Apart from the Baseline v S3 comparison, which revealed differences only for the first 9% of the pull, across all sessions, knee-elbow coordination remained unaltered (Figure 3(d)).

3.2. Group coordination

The augmented information within the biofeedback may only have been of importance to certain individuals, as coordination did not change for some rowers (e.g., $BFb_{90}P5$, Figure 4(a–c)). However, most rowers in this study successfully complied with the biofeedback. Periods of the pull during which changes to technique occurred were consistent for rowers in the BFb_{90} group. Between approximately 40 and 60% of the pull, knee-elbow motions differed from Baseline during S3, and this period was increased to approximately 40–80% of the pull for Baseline v Transfer. Over these periods, rowers made changes to their Baseline coordination, towards that promoted by the biofeedback. The biofeedback intervention therefore influenced similar periods of the pull among the participants rowing

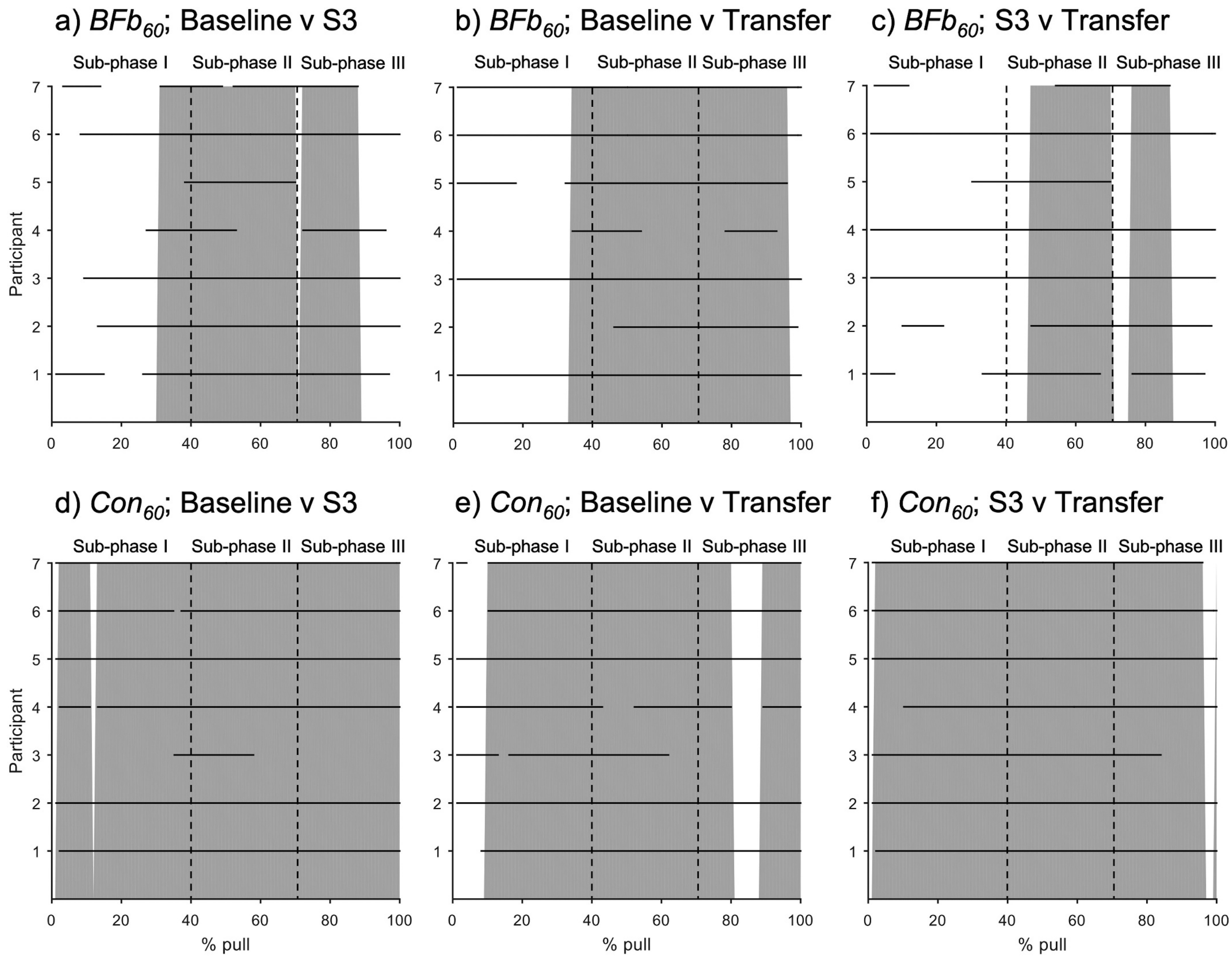

Figure 5. Periods of CI overlap of knee-elbow angle-angle plots for each participant for the low stroke rate (60%) pair comparisons of: (a) BFb_{60}, Baseline v S3; (b) BFb_{60}, Baseline v Transfer; (c) BFb_{60}, S3 v Transfer; (d) Con_{60}, Baseline v S3; (e) Con_{60}, Baseline v Transfer; (f) Con_{60}, S3 v Transfer. Solid horizontal lines indicate overlap between the pair comparisons. Shaded regions indicate where >5 participants have the same temporal overlap, while black shading indicates >5 periods of non-overlap (note, there were no occurrences). Dashed vertical lines represent transitions between pull sub-phases (0–40%, Sub-phase I; 40–70%, Sub-phase II; 70–100%, Sub-phase III).

at higher SRs. Notably, within-group modifications to the pull were maintained when rowing maximally without biofeedback, as indicated by the increased high similarity of the S3 and Transfer movement patterns. Across all comparisons, a lack of coordinative change was indicated by a large proportion of rowers in Con_{90} demonstrating overlap between 21 and 97% of the pull, except for $Con_{90}P4$ (Figure 4(d)). Thus, the rowing technique performed in both S3 and Transfer was like that of Baseline.

Whilst complying with biofeedback at lower SRs, coordination changes appeared mainly during sub-phase I of the pull. Baseline v S3 within-group overlap was less for rowers in BFb_{60} than for rowers in Con_{60} over this period as the BFb_{60} participants demonstrated some individual CI non-overlap during the first 20% and the last 10% of the pull (Figure 5(a)), closer to transition phases at the start and end of the strokes. For the Baseline v Transfer comparison, there was also poor inter-participant agreement during sub-phase I of the pull for rowers in BFb_{60}. This demonstrates common timings of the movement pattern differences amongst this group.

There was also poor S3 v Transfer overlap during sub-phase I of the pull for rowers complying with biofeedback at lower SRs. This shows differences in the movement patterns of S3 and Transfer and suggests less consistent maintenance of the movement patterns induced by the biofeedback. For example, $BFb_{60}P5$ demonstrated Baseline v S3 coordination differences for the first 36% of the pull because of increased elbow extension, and further differences for the last 31% due to increased knee extension. The movement patterns of Baseline v Transfer, however, showed little coordinative difference, which demonstrated a lack of maintenance of alterations that were apparent during S3. Furthermore, the coordination patterns of S3 v Transfer indicated no adaptation to a new coordination pattern with an increase in SR, but a reversion back towards that of Baseline. With the slight exception of between 81 and 88% of the pull between Baseline and Transfer, the techniques of rowers in Con_{60} appeared to remain unaltered by varying SRs as high within-group agreement was apparent across all sessions.

Table 1. Stroke rate, distance and change in distance rowed (Mean ± SD) during 5-minute maximal volitional effort trials at Baseline and Transfer, and either 60% or 90% of baseline stroke rate during intervention session 3 (S3).

	Control			*Biofeedback*			
	Baseline	S3	Transfer	Baseline	S3	Transfer	Interaction
	Con_{60}			BFb_{60}			
SR (S/min)	33 ± 4	22 ± 3*	32 ± 3	35 ± 5	23 ± 2*	34 ± 4	–
Dist (m)	1177 ± 132	1081 ± 131*	1180 ± 136‡	1163 ± 143	1045 ± 86*	1227 ± 96†‡	GxS
δ (%)	–	−8 ± 6	0 ± 2	–	−10 ± 3	6 ± 5	–
	Con_{90}			BFb_{90}			
SR (S/min)	33 ± 3	28 ± 3*	31 ± 4	32 ± 3	29 ± 2*	32 ± 4	–
Dist (m)	1173 ± 135	1129 ± 149*	1190 ± 146‡	1173 ± 141	1133 ± 104	1233 ± 117†‡	GxS
δ (%)	–	−4 ± 2	1 ± 3	–	−3 ± 6	5 ± 4	–

S3, intervention session 3; *Con*, Control; *BFb*, Biofeedback; *SR*, Stroke rate; *Dist*, Distance rowed; δ, change in distance rowed from Baseline. *, Significant within-group difference between Baseline and S3; †, Significant within-group difference between Baseline and Transfer; ‡, Significant within-group difference between S3 and Transfer. Interaction indicates which 3- or 2-way interactions are significant, where GxS is group x session. For all statistical tests $p < 0.05$.

There were no significant three-way interactions for any variable ($p > 0.05$). For *Dist*, there were significant group x session interactions for both lower ($F = 17.09$, $p < 0.01$, $\eta_p^2 = 0.59$) and higher SRs ($F = 16.95$, $p < 0.01$, $\eta_p^2 = 0.55$). Rowers that received biofeedback covered significantly greater distances during Transfer as compared to Baseline (BFb_{60}, $p < 0.01$, $d = 0.43$; BFb_{90}, $p < 0.01$, $d = 0.68$), whereas rowers that received no biofeedback showed no change in the distance rowed (Con_{60}, $p = 0.76$, $d = 0.02$; Con_{90}, $p = 0.74$, $d = 0.03$). For BFb_{60} and rowers in each control group, significantly shorter distances were rowed during S3 compared to Baseline (each $p < 0.02$, $d < 0.24$), whereas BFb_{90} rowed a comparable distance ($p = 0.172$, $d = 0.32$). For all groups, *SR* remained consistent between Baseline and Transfer (BFb_{60}, $p = 0.43$, $d = 0.13$; BFb_{90}, $p = 0.27$, $d = 0.23$; Con_{60}, $p = 0.11$, $d = 0.37$; Con_{90}, $p = 0.53$, $d = 0.15$), however, SR was significantly reduced from Baseline to S3 (BFb_{60}, $p < 0.01$, $d = 3.24$; BFb_{90}, $p = 0.01$, $d = 1.21$; Con_{60}, $p < 0.01$, $d = 3.55$; Con_{90}, $p < 0.01$, $d = 1.39$) (Table 1).

For spatiotemporal parameters of the rowing stroke (Table 2), there were significant group x session Baseline to Transfer interactions for BFb_{90} where S_l ($F = 10.35$, $p < 0.01$, $\eta_p^2 = 0.26$) and P_l ($F = 11.22$, $p < 0.01$, $\eta_p^2 = 0.30$) were significantly increased from Baseline to Transfer (S_l, $p < 0.01$, $d = 1.07$; P_l, $p < 0.01$, $d = 1.06$), whereas BFb_{60} did not change (S_l, $p = 0.67$, $d = 0.04$; P_l, $p = 0.77$, $d = 0.03$). Furthermore, for S_d and S_{dn}, there were significant Baseline to S3 and Baseline to Transfer increases for only BFb_{90} (each $p < 0.02$, $d > 0.71$).

For joint angles, complying with the biofeedback did not alter Elbow Θ_{catch}, which remained consistent across time points at both SRs ($p > 0.05$). The Knee Θ_{catch} decreased and Spine Θ_{catch} increased between Baseline and S3 regardless of the presence of biofeedback or SR. However, these changes were only significant for those that complied with the biofeedback at a lower SR (Knee Θ_{catch}, $p = 0.03$, $d = 0.61$; Spine Θ_{catch}, $p < 0.01$, $d = 0.70$). Between Baseline and Transfer, those that complied with the biofeedback significantly decreased Knee Θ_{catch} at both higher and lower SRs, as did those that rowed at a lower SR without biofeedback. The biofeedback appeared to maintain Spine Θ_{catch} between Baseline and Transfer as Con_{60} and Con_{90} each showed significant increases ($p < 0.01$, $d = 0.96$; $p = 0.01$, $d = 0.63$, respectively). At both high and low SRs, there were no group x session interaction effects for Elbow or Knee Θ_{finish} ($p > 0.05$) and no significant Baseline to Transfer changes in Spine Θ_{finish} were observed ($p > 0.05$).

4. Discussion

The purpose of this study was to assess the effects of SR on the ability of trained rowers to comply with concurrent visual biomechanical biofeedback and to transfer any modifications in the technique to higher SRs and maximal intensity rowing conditions. As this was a biofeedback learning study, SR was used to control the rowing task so that within-group and between-group disparities in the number of iterations were reduced. The settings for the biofeedback were dependent upon joint motion in relation to expected stroke displacement, despite variation in stroke displacement with each cycle. Using current stroke displacement would have meant that the biofeedback was not concurrent as this could only have been ascertained after the completion of the pull. Basing biofeedback on the last stroke (or several previous strokes) would also have been problematic as it could have been suboptimal as the rower attempted to comply to the biofeedback. The objective was to show that biofeedback could enhance requested changes in the technique, which was demonstrated with improvements in adherence to the desired movement pattern (Figure 3) and to distance covered (Table 1). The results of this study, like those of Spinks and Smith (1994), Anderson et al. (2005), and Schaffert et al. (2011), demonstrate that biofeedback was effective in guiding changes to more skilled rowing technique. This was characterised by a modification of the coordination of knee and elbow motions.

4.1. Coordination pattern changes

Complying with biofeedback at a lower SR induced few discrete kinematic variable change (Table 2); hence, other factors such as motivational benefits (Weakley et al., 2019) may explain improvements in distance rowed (Table 1). However, using CI2, kinematic changes were identified across the times series with more improvements in both *BFb* groups than the *control* groups (Figures 4 and Figure 5). These CI2 analyses suggest that biofeedback was effective in altering the targeted kinematic variables as opposed to improvements arising from other factors such as motivation. It is proposed that CI2, that is independent of the statistical significance, provides an additional tool to help explore changes in kinematic time-series data.

Individual responses to biofeedback are not often documented. Mullineaux et al. (2012) indicated qualitative differences in

Table 2. Spatiotemporal parameters and joint angles at the catch and finish (Mean ± SD) of the rowing stroke during 5-minute maximal volitional effort trials at Baseline and Transfer, and either 60% or 90% of baseline stroke rate during intervention session 3 (S3).

	Control			*Biofeedback*			
	Baseline	S3	Transfer	Baseline	S3	Transfer	Interaction
	Con_{60}			BFb_{60}			
S_l (m)	2.85 ± 0.26	2.80 ± 0.38	2.83 ± 0.25	2.60 ± 0.31	2.92 ± 0.24	2.90 ± 0.29	–
P_l (m)	1.44 ± 0.13	1.40 ± 0.18	1.42 ± 0.12	1.31 ± 0.14	1.45 ± 0.13	1.45 ± 0.16	–
S_d (m)	1.36 ± 0.14	1.36 ± 0.19	1.37 ± 0.13	1.23 ± 0.11	1.40 ± 0.14	1.39 ± 0.17	–
S_{dn} (%BH)	81 ± 5	81 ± 6	82 ± 3	78 ± 8	84 ± 8	83 ± 9	–
	Con_{90}			BFb_{90}			
S_l (m)	2.97 ± 0.26	2.99 ± 0.30	2.98 ± 0.29	2.83 ± 0.21	2.95 ± 0.20*	2.98 ± 0.15†	GxS
P_l (m)	1.50 ± 0.13	1.50 ± 0.14	1.50 ± 0.14	1.41 ± 0.11	1.49 ± 0.09*	1.51 ± 0.07†	GxS
S_d (m)	1.42 ± 0.11	1.44 ± 0.13	1.45 ± 0.13	1.35 ± 0.09	1.42 ± 0.10*	1.44 ± 0.07†	GxS
S_{dn} (%BH)	83 ± 4	84 ± 4	84 ± 5	80 ± 6	84 ± 7*	85 ± 6†	GxS
Θ_{catch} (°)	Con_{60}			BFb_{60}			
Elbow	151 ± 4	153 ± 4	153 ± 7	156 ± 7	157 ± 6	156 ± 6	–
Knee	68 ± 10	67 ± 6	65 ± 6	68 ± 8	64 ± 8*	62 ± 11†	–
Spine	65 ± 8	70 ± 5	70 ± 5†	68 ± 6	73 ± 5*	74 ± 9	–
	Con_{90}			BFb_{90}			
Elbow	153 ± 5	156 ± 4	153 ± 3	156 ± 5	158 ± 8	157 ± 6	–
Knee	67 ± 8	63 ± 9	62 ± 10†	73 ± 10	69 ± 12	67 ± 12†	–
Spine	67 ± 6	73 ± 8	73 ± 9†	76 ± 11	80 ± 13	79 ± 13	–
Θ_{finish} (°)	Con_{60}			BFb_{60}			
Elbow	53 ± 8	53 ± 7	54 ± 8	47 ± 6	46 ± 11	47 ± 7	–
Knee	162 ± 4	166 ± 4*	164 ± 7	167 ± 4	165 ± 4	164 ± 7	–
Spine	141 ± 7	136 ± 7	137 ± 6	134 ± 8	139 ± 7	139 ± 12	GxS
	Con_{90}			BFb_{90}			
Elbow	55 ± 6	50 ± 7	52 ± 7	51 ± 7	50 ± 7	51 ± 6	–
Knee	159 ± 8	168 ± 5	162 ± 7	166 ± 4	163 ± 7	163 ± 7	–
Spine	137 ± 11	138 ± 9	147 ± 11†	135 ± 14	144 ± 9	135 ± 21	–

S3, intervention session 3; *Con*, Control; *BFb*, Biofeedback; S_l, Stroke length; P_l, Pull length; S_d, Stroke displacement; S_{dn}, Normalised stroke displacement; BH, Body height; Θ_{catch}, Angle at catch; Θ_{finish}, Angle at finish; *, Significant within-group difference between Baseline and S3; †, Significant within-group difference between Baseline and Transfer; ‡, Significant within-group difference between S3 and Transfer. Interaction indicates which 3- or 2-way interactions are significant, where GxS is group x session. For all statistical tests $p < 0.05$.

interactions with biofeedback in top-level rifle shooters, and Eriksson et al. (2011) quantitatively reported individual attempts to alter running mechanics and identified one participant who did not adjust the technique. Similarly, the approach in this study proved beneficial for exploring consistency of inter-participant responses to biofeedback (e.g., Figures 4 and Figure 5). As rowing techniques vary between individuals, there are potentially no general optimal parameters that all rowers should exhibit (Lamb, 1989), yet most of the rowers that received biofeedback did alter their coordination. For those that did not comply, the content of the biofeedback possibly did not match the constraints of the imposed task well enough (Fowler & Turvey, 1978). For these rowers, whilst increasing their error-detection capabilities by supplementing intrinsic feedback with regard to the general movement pattern (Schmidt, 1991), the biofeedback possibly did not provide information that was specific enough concerning the degree of error in the technique (information was only provided if the movement pattern was incorrect, i.e., elbow flexion occurred too early). Transitional information about how to achieve the desired coordination (Kernodle & Carlton, 1992), or providing a criterion response of the desired pattern that the rowers would aim to match (Smith & Loschner, 2002), may have alleviated this through integration of increased error detection with how to adapt technique. However, incorporating such a strategy into this intervention could increase dependency properties of the biofeedback (Wulf et al., 1998).

Unlike many other learning studies (e.g., Wulf et al., 1998), the ability to perform the general movement pattern (the rowing stroke) existed before biofeedback was provided. Changes were therefore not a move towards new technique, but were a refinement of an established one, and modifications to the technique are potentially subtler in more proficient performers. A cumulative summation of a marginal increase in the performance of each stroke could account for the increase in the distance covered after 5 min, especially given the high number of repetitions of the rowing stroke completed during Transfer.

4.2. Effects of exercise intensity on biofeedback response

This is the first study to investigate the effects of SR on the ability to comply with a single biofeedback intervention to alter rowing kinematics. The guiding properties of this biofeedback appeared unaffected by intensity during acquisition, as *Dist* increased and most rowers that received biofeedback modified coordination. These findings are consistent with studies that have shown the benefits of biofeedback when rowing both at higher (Anderson et al., 2005) and low SRs (Schaffert et al., 2011). It appears that this biofeedback did not force the correction of task-irrelevant or single-cycle errors (Wei & Körding, 2009), but facilitated the modification of systematic movement errors that reoccurred during each cycle (Sigrist et al., 2013). However, the specific response to the biofeedback was inconsistent between SRs.

Complying with biofeedback at higher SRs induced changes to spatiotemporal parameters that were not seen at lower SRs between Baseline and S3. Additionally, greater periods of coordinative similarity in Baseline v S3 differences between 40 and 64% of the pull were apparent for rowers that complied with biofeedback at higher SRs, compared to lower SRs. However, for those that received biofeedback at lower SRs, there was greater temporal difference in Baseline v S3 comparisons over the first 40% of the pull. While the general ability to comply with this biofeedback was not diminished, differences in temporal aspects of coordination changes indicate that SR influenced how the information in the biofeedback was used. Coordination changes over the early stages of the pull could have been affected by a change in rowing task demands at different SRs (McGregor et al., 2004), or the need to generate increased force to accelerate the ergometer-system to overcome inertia at the catch and produce higher SRs (Martin & Bernfield, 1980). This is consistent with the work of Lintmeijer et al. (2019), who demonstrated that power output feedback aided crew rowers in meeting power output targets, but differences in consistency of power output improvements were apparent between rowing intensities.

4.3. Effects of exercise intensity on transfer of movement patterns

Spatiotemporal changes made to the stroke by BFb_{90} appeared to be maintained from S3 to Transfer, and rowers in both groups that received biofeedback managed to successfully transfer coordination changes to the rowing stroke to conditions of maximal intensity rowing when the biofeedback was removed. Thus, during acquisition, alongside the biofeedback guiding movement pattern alterations, intrinsic feedback mechanisms may have been developed sufficiently to be used for error correction in place of the biofeedback during Transfer (Schmidt, 1991). During the Transfer test, rowers in BFb_{90} and BFb_{60} rowed significantly greater distances than during Baseline (Table 1).

While positive benefits of the biofeedback were apparent for rowers who complied with biofeedback at higher and lower SRs, S3 v Transfer analysis revealed between-group differences in the transfer of newly developed coordination patterns to maximal performance. For rowers in BFb_{90}, individual coordination patterns showed high coordinative similarity (Figure 4(c)), which indicates little reversion back towards the pattern of Baseline. The purported effects of the guidance hypothesis were therefore not apparent, as reliance on the biofeedback for the reproduction of the modified movement pattern had not developed, as has been reported in complex tasks (e.g., Sigrist et al., 2013). As such, performance did not appear to integrate with the augmented visual information available (Moradi et al., 2014) and was not processed as part of the task (Proteau et al., 1992), during acquisition conditions that were similar to Transfer. While rowing at a maximal exercise intensity, where the effects of the intervention would need to be replicated, this intervention did not induce a significant dependency (Salmoni et al., 1984; Schmidt, 1991).

For rowers that complied with biofeedback at lower SRs, less intrinsic response-produced sensory (e.g., kinaesthetic) information regarding maximal intensity rowing may have been available. This could account for reversion back to Baseline patterns for some participants due to a potential failure to develop suitable intrinsic error-detection capabilities that could have been used to adapt performance into Transfer (Schmidt, 1991). This shows an acquisition effect of the biofeedback for rowers that complied to the biofeedback at a lower SR, demonstrating a lack of adaptability of the newly learnt movement pattern. This supports both the guidance hypothesis (Salmoni et al., 1984) and the hypothesised specificity effect of such interventions (Blandin et al., 2008; Proteau et al., 1992; Ranganathan & Newell, 2009).

The findings of this study show that the intensity of exercise performed whilst complying with biofeedback does influence the ability of trained rowers to transfer technique changes from acquisition to more functionally relevant tasks (Wu et al., 2015). Given the specificity of the newly acquired coordination changes (Ranganathan & Newell, 2009), such patterns appear explicitly linked to the conditions under which they are learnt. Therefore, the performance is improved to the extent that acquisition and transfer conditions are similar (Winstein & Schmidt, 1990). Complying with biofeedback at a SR that is closer to the maximal capacity of the rower appears to facilitate the transfer of newly learnt movement patterns to conditions of maximal intensity. Learning of complex tasks with biofeedback could therefore be most effective when acquisition conditions closely resemble the performance and task conditions that will be encountered once biofeedback is removed.

5. Conclusions

Biomechanical biofeedback on joint sequencing is a useful training aid for skilled rowers, whereby some rowers successfully adapted joint motion sequencing patterns during the rowing stroke. Compliance with biofeedback was SR dependent, supporting the specificity hypothesis such that more similar conditions during the biofeedback task to maximal, competition-intensity rowing resulted in improved performance and retention. The specificity of the biofeedback task and the exercise intensity at which it is performed is worth considering in the development of biofeedback training.

Disclosure statement

The authors report no conflict of interest.

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